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A PRACTICAL FIELD WIND COMPENSATION TECHNIQUE FOR UNGUIDED ROCKETS

by
Gordon L. Dunaway



ATMOSPHERIC SCIENCES RESEARCH OFFICE
WHITE SANDS MISSILE RANGE, NEW MEXICO

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UNITED STATES ARMY ELECTRONICS COMMAND

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ABSTRACT

An accurate and rapid wind compensation technique for the field determination of launcher settings for unguided rockets is presented. The method was tested with a five-degree-of-freedom trajectory simulation program using several observed wind profiles. The results of five computer tests for an Aerobee 150 show that the maximum theoretical impact miss was 3.8 statute miles when the theoretical impact displacement was 147.4 statute miles. In three tests for an Athena (two-stage), the maximum theoretical impact miss was 5.4 statute miles when the theoretical impact displacement due to the wind was 141.8 statute miles.

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INTRODUCTION

Since the beginning of rocketry, the need has existed for a rapid and practical method of applying wind compensation corrections to unguided rockets. This is particularly true in the case of unguided rockets carrying scientific payloads to extremely high altitudes when safety and recovery considerations place constraints on the impact area and in the case of tactical missiles carrying warheads to pre-determined targets.

Utilization of high-speed computers during the past few years has made possible the development of highly sophisticated rocket trajectory simulation models. When accurate rocket descriptors, atmospheric data and initial conditions are used in these models, the rocket trajectories from launch to impact can be closely simulated.

These trajectory simulation models have been the basis for the development of various techniques (1-11) for wind effect compensation, each showing certain advantages and disadvantages in operational usage.

An accurate operational procedure is the meteorological real-time system (12,13,14) developed by the Atmospheric Sciences Laboratory at White Sands Missile Range (WSMR), New Mexico. This procedure is used in the support of Athena rockets which are fired from Green River, Utah, to impact on WSMR. For this system, data from wind measuring instrumentation at the launch site are transmitted over commercial data lines to a digital computer at the headquarters area of the missile range. The computer reduces the wind data, applies them to a trajectory model, computes launcher settings using iterative techniques, and prints out a complete rocket trajectory simulation for each wind profile considered. This type of system would be desirable for all unguided rocket firings; however, because of cost and inaccessibility to remote sites, the real-time system may be impractical in some cases.

One of the most widely accepted field wind compensation techniques to date is the graphical method developed by James (3), in which trajectories are computed to determine the launcher setting corrections necessary to compensate for given wind profiles. Nomograms which show ballistic wind speed and direction versus desired launcher azimuth and elevation angles are used for the given rocket. The method works quite well for high-angle trajectories; however, there is some problem in the interpolation of the wind speed on the nomograms, and the validity of the wind-weighting factors suggested for this method is questioned for low-angle trajectories. Also, additional time is required to convert the ballistic wind components to speed and direction, and time is of the essence due to the low-level wind variability.

The technique presented in this report is similar to that of James (3). Instead of nomograms, tables of ballistic wind components versus desired launcher azimuth and elevation angles, theoretical no wind impact, and theoretical range and cross displacement of impact due to wind for a given range and interval of ballistic wind components are used. The basic theory used with this technique is very close to that described by Duncan and Engebos (7).

The wind-weighting technique used with this system is based on deviations of the rocket impacts due to wind acting on the rocket during its ascent and descent through various altitude layers (10), whereas the wind-weighting for the James method is based on cross-wind-induced angular deviations at the altitudes to which the wind effect is considered to be significant.

DISCUSSION

The major weaknesses in the field wind compensation techniques (7,15) used in the past at WSMR have been: (1) the assumption of linear relationships between ballistic wind components and impact displacements due to wind and (2) the assumption of linear relationships between small changes in elevation angles and changes in impact range.

When the rockets are launched near the vertical, these assumptions are reasonably valid, and the method can be used with a fair degree of accuracy. As the nominal elevation angle is lowered, the results based on these assumptions deteriorate markedly.

Experiments have shown that when the nominal launcher elevation angle is greater than that required for a maximum range trajectory, the wind-weighting curve derived from cross-wind-induced impact deviations is very similar to that derived from range-wind-induced impact deviations. A high degree of accuracy is obtained if a single set of wind-weighting factors is used to compute both components of ballistic winds for this type of trajectory.

As the nominal elevation angle is decreased from the angle required for a maximum range trajectory, the wind-weighting curve for range winds begins to differ significantly from that for cross winds. Thus, separate sets of wind-weighting factors should be applied to the range-wind and cross-wind components in ballistic wind computations for trajectories of this type.

DEVELOPMENT

Assume a right-hand coordinate system with the origin at the launcher. The y-axis is positive in the direction of the firing line,

the x-axis is positive to the right of the firing line, and the z-axis is positive upward. Let γ and ψ represent angles in the vertical planes parallel and perpendicular to the firing line, respectively (7). See Figure 1.

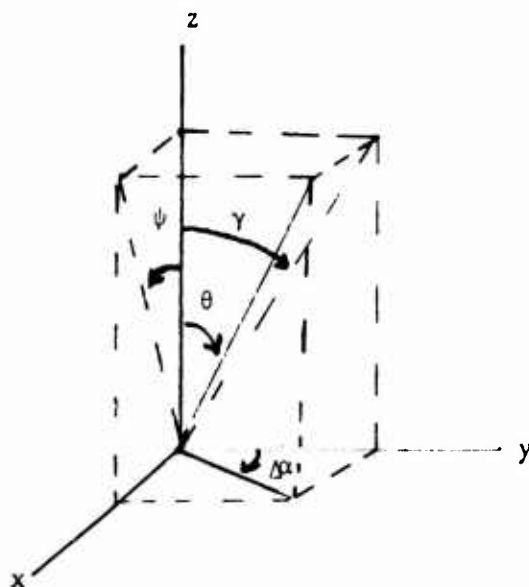


Figure 1

Then,

$$\gamma_L = \tan^{-1} [\tan \theta_L \cos (\alpha_L - \alpha_{Lo})]$$

and

$$\psi_L = \tan^{-1} [\tan \theta_L \sin (\alpha_L - \alpha_{Lo})] \quad (1)$$

where γ_L and ψ_L are the launcher angles in the vertical planes parallel and perpendicular to the firing line referenced to the nominal launcher azimuth, α_{Lo} is the nominal launcher azimuth, α_L is the actual launcher azimuth, and θ_L is the launcher elevation angle from vertical.

Similarly

$$\gamma_B = \tan^{-1} [\tan \theta_B \cos (\alpha_B - \alpha_{Lo})]$$

and

$$\psi_B = \tan^{-1} [\tan \theta_B \sin (\alpha_B - \alpha_{Lo})] \quad (2)$$

where γ_B and ψ_B are the angles in the vertical planes parallel and perpendicular to the firing line of the velocity vector at burnout referenced to the nominal launcher azimuth, α_L is the azimuth of the velocity vector at burnout, and θ_B is the elevation angle from vertical of the velocity vector at burnout.

Let U and V represent the east-west and north-south components of ballistic wind, respectively. Then,

$$U_L = U \cos \alpha_{Lo} - V \sin \alpha_{Lo}$$

and

$$V_L = U \sin \alpha_{Lo} - V \cos \alpha_{Lo} \quad (3)$$

where U_L and V_L are the cross and range components of ballistic wind referenced to the nominal launcher azimuth.

The following assumptions are used in the development of this technique:

1. Changes in γ_L vary linearly with respect to changes in γ_B for no wind trajectories, although the relationship may be different for increasing than for decreasing changes.
2. Changes in ψ_L vary linearly with respect to changes in ψ_B for no wind trajectories.
3. Changes in γ_B vary linearly with respect to changes in V_L , although the changes may be different for a head-wind than for a tail-wind.
4. Changes in ψ_B vary linearly with respect to changes in U_L .

Factors relating changes in launcher angles to changes in burnout angles can be determined using the first two assumptions and a small set of no wind trajectory simulations with appropriate launcher settings:

$$\left(\frac{d\gamma_L}{d\gamma_B}\right)_t = \frac{\gamma_{Lt} - \gamma_{Lo}}{\gamma_B - \gamma_{Bo}}$$

$$\left(\frac{d\gamma_L}{d\gamma_B}\right)_h = \frac{\gamma_{Lh} - \gamma_{Lo}}{\gamma_B - \gamma_{Bo}}$$

and

$$\left(\frac{d\psi_L}{d\psi_B}\right)_c = \frac{\psi_L - \psi_{L,0}}{\psi_B - \psi_{B,0}} \quad (4)$$

where the subscripts t and h represent changes in γ with respect to decreasing or increasing elevation angles as would be experienced with a tail-wind or a head-wind, respectively, and the subscript c represents changes in ψ as would be experienced with a cross-wind.

Similar factors relating changes in burnout angles to changes in ballistic wind can be determined using the third and fourth assumptions and a small set of trajectory simulations with nominal launcher settings and appropriate wind inputs:

$$\left(\frac{d\gamma_B}{dV_L}\right)_t = \frac{\gamma_{Bt} - \gamma_{Bo}}{V_{Lt}}$$

$$\left(\frac{d\gamma_B}{dV_L}\right)_h = \frac{\gamma_{Bh} - \gamma_{Bo}}{V_{Lh}}$$

and

$$\left(\frac{d\psi_B}{dU_L}\right)_c = \frac{\psi_B - \psi_{Bo}}{U_L} \quad (5)$$

Combining the factors from Eq. (4) with those from Eq. (5), we obtain the factors which will give the desired change in γ_L with respect to a change in tail-wind or head-wind component of ballistic wind and the desired change in ψ_L with respect to a change in cross-wind component of ballistic wind:

$$\left(\frac{d\gamma_L}{dV_L}\right)_t = \left(\frac{d\gamma_L}{d\gamma_B}\right)_t \cdot \left(\frac{d\gamma_B}{dV_L}\right)_t$$

$$\left(\frac{d\gamma_L}{dV_L}\right)_h = \left(\frac{d\gamma_L}{d\gamma_B}\right)_h \cdot \left(\frac{d\gamma_B}{dV_L}\right)_h$$

and

$$\left(\frac{d\psi_L}{dU_L}\right)_c = \left(\frac{d\psi_L}{d\psi_B}\right)_c \cdot \left(\frac{d\psi_B}{dU_L}\right)_c \quad (6)$$

These factors, Eq. (6), are used as the basis for launcher angle corrections in the following manner:

$$\Delta \gamma_L = V_L \left(\frac{d\gamma_L}{dV_L} \right)_t, \quad V_L < 0$$

$$\Delta \gamma_L = V_L \left(\frac{d\gamma_L}{dV_L} \right)_h, \quad 0 \leq V_L$$

and

$$\Delta \psi_L = U_L \left(\frac{d\psi_L}{dU_L} \right)_c \quad (7)$$

The desired launcher angles referenced to the nominal launcher azimuth then become:

$$\gamma_L = \gamma_{Lo} - \Delta \gamma_L$$

and

$$\psi_L = \Delta \psi_L \quad (8)$$

The angles are then converted to azimuth and elevation angles in the following manner:

$$\Delta \alpha_L = \tan^{-1} \left[\frac{\tan \psi_L}{\tan (\gamma_{Lo} - \Delta \gamma_L)} \right]$$

$$\alpha = \alpha_{Lo} - \Delta \alpha_L$$

and

$$\theta = \tan^{-1} \left[\frac{\tan (\gamma_{Lo} - \Delta \gamma_L)}{\cos (\Delta \alpha_L)} \right] \quad (9)$$

where α and θ are the desired launcher azimuth and elevation angles, respectively.

The impact range versus launcher elevation angle for a no wind trajectory can be closely approximated over reasonable interval by the parabola,

$$R_n = a\theta - b \quad (10)$$

where R_n is the no wind range, θ is the launcher elevation angle from vertical and a and b are constants which can be determined from a small set of no wind trajectory simulations.

It is desirable to have a method for obtaining theoretical impact displacements due to wind so that the expected impact dispersion due to wind variability may be assessed.

Close approximations to the theoretical impact displacements due to wind are given by,

$$\begin{aligned} Y_{Lw} &= Y_{LO} - R_n \cos \alpha_L - C_y \\ \text{and} \quad X_{Lw} &= X_{LO} - R_n \sin \alpha_L - C_x \end{aligned} \quad (11)$$

where Y_{Lw} and X_{Lw} are the range and cross components of the theoretical impact displacement due to wind, Y_{LO} and X_{LO} are the range and cross components of the nominal impact, and C_y and C_x are the range and cross components of the theoretical impact displacement due to the rotation of the earth.

EVALUATION TESTS

To evaluate the accuracy of the technique, tests were performed using wind measurements and theoretical rocket descriptors from actual WSMR support missions. A five-degree-of-freedom trajectory simulation program (10) and a high-speed computer were used for these tests.

One series was performed for an Aerobee 150 vehicle with a nominal elevation angle of 3 degrees from vertical. Five observed wind profiles (Appendix A) were used for these tests.

Launcher settings derived using this technique, the observed wind profiles, and theoretical rocket performance parameters were put in the program and trajectories were computed. The impacts from the computer trajectories were compared with the nominal impacts to determine the accuracy of the technique. The results are presented in Table I.

Results of five tests for the Aerobee 150 indicated a maximum theoretical impact miss from the use of this method of 3.8 statute miles, which occurred when the theoretical impact displacement due to wind was 147.4 statute miles.

The Aerobee 150 results were so encouraging that similar tests were run for a higher performance vehicle (Athena, two-stage) with a

TABLE I
Results from tests of Aerobee 150 Launcher Settings for Various Wind Profiles

CASE	BALLISTIC WIND COMPONENTS (MPH)		LAUNCHER SETTINGS COMPUTED USING THIS TECHNIQUE (DEGREES)		THEORETICAL IMPACT FROM 5-DEGREE-OF-FREEDOM TRAJECTORY SIM. (ST. MILES)		THEORETICAL IMPACT MISS DISTANCE FROM THE USE OF THIS TECHNIQUE (ST. MILES)		THEORETICAL IMPACT DISPLACEMENT DUE TO WIND, BASED ON A UNIT WIND EFFECT (ST. MILES)	
	RANGE	CROSS	AZ	EL	RANGE	CROSS	RANGE	CROSS	RANGE	CROSS
NOMINAL	0.00	0.00	360.0	87.0	56.70	-5.56	0.00	0.00	0.00	0.00
1	-9.38	-10.43	024.8	84.5	57.39	-4.44	0.69	1.12	-38.56	-44.23
2	11.91	1.46	321.8	89.5	57.33	-5.00	0.63	0.56	48.96	6.20
3	0.72	-26.42	064.4	83.4	57.24	-2.40	0.54	3.16	2.97	-112.00
4	-5.29	-34.39	061.8	81.3	57.73	-1.95	1.03	3.61	-21.76	-145.82
5	-3.58	- 2.23	007.5	86.2	55.41	-4.33	-1.29	1.23	-14.73	-9.45

NOTE: All wind and impact data are referenced to the no wind launcher azimuth.

nominal elevation angle of 15 degrees from vertical. Three observed wind profiles (Appendix B) were used for these tests. The results are presented in Table II; the maximum theoretical impact miss was 5.4 statute miles which occurred when the theoretical impact displacement due to wind was 141.8 statute miles.

CONCLUSIONS

This wind compensation technique is believed to be practical, not only as an accurate field wind compensation technique, but also as a close first approximation to be used in meteorological real-time support programs.

Once the tables have been constructed for a given rocket, the only additional data needed to look up corrected launcher settings are the ballistic wind components. Thus, on-the-site calculations are minimized, and corrected launcher settings can be determined rapidly.

TABLE II
Results from Tests of Athena Launcher Settings for Various Wind Profiles

CASE	BALLISTIC WIND COMPONENTS (MPH)		LAUNCHER SETTINGS COMPUTED USING THIS TECHNIQUE (DEGREES)		THEORETICAL IMPACT FROM 5-DEGREE-OF-FREEDOM TRAJECTORY SIM. (ST. MILES)		THEORETICAL IMPACT MISS DISTANCE FROM THE USE OF THIS TECHNIQUE (ST. MILES)		THEORETICAL IMPACT DISPLACEMENT DUE TO THE WIND, BASED ON A UNIT WIND EFFECT (ST. MILES)	
	RANGE	CROSS	AZ	EL	RANGE	CROSS	RANGE	CROSS	RANGE	CROSS
NOMINAL	0.00	0.00	151.7	75.0	443.96	13.39	0.00	0.00	0.00	0.00
1	0.79	18.94	136.4	74.6	444.87	13.62	0.91	0.23	1.45	119.38
2	13.79	17.79	134.6	77.0	444.18	9.54	0.22	-3.85	25.31	112.13
3	6.73	22.42	132.4	74.5	446.62	8.71	2.66	-4.68	12.35	141.31

NOTE: All wind and impact data are referenced to the no wind launcher azimuth.

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APPENDIX A

WIND PROFILES USED FOR AEROBEE 150 TESTS

ALTITUDE LAYER (FT 'ISL)	MEAN WIND COMPONENTS (MPH)									
	1		2		3		4		5	
	+N-S	+E-W	+N-S	+E-W	+N-S	+E-W	+N-S	+E-W	+N-S	+E-W
4143-	-2.5	-3.0	6.5	9.5	4.0	-17.0	-0.5	-18.0	-4.0	-1.0
4250-	-3.0	-9.0	4.0	7.0	2.0	-19.0	-0.5	-20.0	-4.0	-0.5
4400-	-1.5	-8.0	4.0	6.0	0.5	-22.0	1.5	-27.5	-4.5	-0.5
4600-	1.0	-7.0	11.0	4.0	0.0	-23.0	-0.5	-27.5	-7.5	0.0
4800-	-3.5	-6.0	16.0	1.5	0.5	-22.0	-1.5	-31.0	-7.5	2.0
5200-	-8.0	-14.0	21.5	-2.5	1.5	-21.0	2.5	-31.0	-4.0	7.5
5600-	-2.5	-18.0	23.5	-3.5	2.5	-22.0	4.0	-35.0	-4.0	12.5
6000-	-1.0	-14.0	16.0	0.0	3.0	-29.0	4.5	-40.0	-3.0	16.5
6500-	-3.0	-13.0	12.0	2.0	8.0	-30.5	2.5	-37.0	-5.5	15.5
7000-	-5.0	-6.0	10.0	0.5	8.5	-31.5	2.5	-35.0	-8.0	13.0
7500-	-3.5	-6.0	10.0	-1.5	8.0	-32.0	4.0	-46.0	-9.0	13.0
8000-	-5.8	-15.0	11.5	0.0	0.0	-33.4	0.0	-43.8	0.0	20.7
9000-	-16.1	-9.2	3.1	-2.9	-6.3	-37.4	-15.5	-43.2	8.6	7.5
14000-	-26.5	0.0	12.1	-10.4	4.0	-21.3	-19.0	-51.8	6.9	-18.4
19000-	-36.9	-13.2	29.4	-5.2	12.1	-33.4	-15.5	-88.1	0.0	-21.9
24000-	-41.5	-34.5	56.4	9.8	0.0	-56.4	-18.4	-105.4	-13.2	-35.7
29000-	-45.6	-39.2	70.2	0.0	-13.8	-79.5	-28.2	-78.3	-18.4	-50.7
34000-	-55.3	-46.6	50.1	-8.6	-31.1	-84.1	-32.8	-57.0	-17.8	-49.5
39000-	-68.5	-57.6	34.0	-19.6	-26.5	-73.7	-43.8	-51.8	-15.5	-43.2
44000-	-42.0	-35.7	26.5	-31.7	-11.5	-65.6	-53.0	-63.3	-12.6	-34.5
49000-	-34.5	-28.8	26.5	-31.7	-9.8	-55.9	-40.3	-69.7	-10.4	-28.8
54000-	-16.7	-9.8	10.9	-19.0	23.0	0.0	-36.9	-21.3	-12.1	-6.9
64000-	-6.9	0.0	2.3	-13.8	6.9	2.3	-21.9	-26.5	5.8	-1.2
74000-	-5.2	2.9	8.1	-21.8	0.0	6.9	-12.1	-13.8	2.9	-8.1
84000-	-8.1	-4.6	2.9	-32.2	-9.8	-3.5	-12.7	0.0	9.8	-8.1
94000- 104000	-23.6	-13.2	1.2	-46.1	-5.2	6.3	-8.1	6.9	3.5	-19.0

APPENDIX B

WIND PROFILES USED IN ATHENA TESTS

ALTITUDE LAYER (FT MSL)	MEAN WIND COMPONENTS (MPH)					
	1		2		3	
	+N-S	+E-W	+N-S	+E-W	+N-S	+E-W
4493- 4515	-6.9	-3.4	-8.1	-7.5	-6.6	-4.5
4515- 4549	-6.2	-4.1	-6.6	-12.1	-11.6	-5.4
4549- 4593	-5.8	-5.1	-8.8	-10.0	-17.0	-2.2
4593- 4638	-5.3	-6.5	-9.7	-9.8	-18.3	-6.7
4638- 4702	-5.0	-7.5	-8.4	-11.1	-17.4	-10.5
4702- 4789	-4.3	-8.3	-11.6	-10.9	-18.3	-12.4
4789- 4873	-3.0	-9.4	-15.2	-10.6	-19.3	-9.2
4873- 4968	-2.5	-10.8	-15.7	-9.5	-17.2	-10.5
4968- 5000	-1.8	-11.7	-14.9	-12.2	-16.7	-8.9
5000- 5100	-1.2	-12.7	-14.3	-12.2	-13.2	-10.7
5100- 5200	-2.2	-13.5	-15.6	-11.6	-13.5	-8.5
5200- 5300	-2.7	-14.9	-17.8	-11.9	-12.6	-10.7
5300- 5400	-3.4	-15.4	-18.3	-9.2	-13.8	-12.2
5400- 5500	-4.2	-16.5	-15.5	-11.2	-14.3	-15.9
5500- 5750	-5.0	-17.4	-16.5	-13.2	-17.4	-13.4
5750- 6000	-6.1	-18.7	-17.1	-19.3	-14.8	-19.3
6000- 6250	-7.2	-19.8	-17.1	-11.0	-20.0	-21.7
6250- 6500	-8.4	-20.5	-19.1	-11.3	-19.2	-20.6
6500- 7000	-9.6	-21.0	-18.3	-9.1	-16.7	-19.3
7000- 7500	-10.3	-21.2	-19.0	-10.9	-17.5	-20.9
7500- 8000	-10.6	-21.1	-19.1	-9.5	-14.8	-19.3
8000- 8926	-10.7	-21.1	-19.5	-7.5	-16.5	-23.7
8926-11446	-11.3	-20.1	-19.0	-1.5	-16.6	-21.7

APPENDIX B (CONT)

WIND PROFILES USED IN ATHENA TESTS

ALTITUDE LAYER (FT. MSL)	MEAN WIND COMPONENTS (MPH)					
	1		2		3	
	+N-S	+E-W	+N-S	+E-W	+N-S	+E-W
11446- 13446	-14.6	-19.6	-26.0	2.9	-14.8	-17.8
13446- 15000	-18.6	-20.2	-6.7	15.3	-18.3	-21.7
15000- 17000	-21.6	-21.7	-49.5	-1.3	-31.1	-12.2
17000- 19000	-25.7	-23.0	-54.1	-1.4	-25.5	-15.6
19000- 21000	-29.5	-23.9	-66.8	-1.7	-27.5	-16.8
21000- 23000	-31.8	-24.5	-65.4	-25.7	-26.7	-23.6
23000- 25000	-34.5	-25.0	-71.8	-28.3	-28.5	-25.2
25000- 30000	-33.2	-41.0	-72.7	-44.5	-22.9	-28.8
30000- 35000	-28.5	-61.0	-73.3	-64.8	-30.2	-55.7
35000- 45000	-21.5	-57.0	-59.5	-52.6	-10.6	-70.6
45000- 55000	-1.0	-42.2	-20.8	-26.1	-6.1	-41.0
55000- 65000	12.0	-19.0	3.4	-16.9	-1.9	-12.5
65000- 75000	18.8	-13.2	10.2	2.1	2.7	-2.2
75000- 85000	17.5	-11.0	-0.3	12.7	2.3	-11.3
85000- 95000	-1.0	-21.3	-5.5	13.9	-3.2	-21.6
95000-105000	0.6	-28.5	-5.1	12.9	6.2	-30.5
105000-115000	3.5	-34.5	-8.4	21.4	5.6	-37.6
115000-135000	-1.0	-34.3	-7.6	19.3	-4.2	-36.6
135000-155000	-3.9	-19.2	-14.8	37.5	-3.7	-25.1
155000-175000	-7.5	12.0	-15.6	76.7	-4.1	20.3
175000-195000	-9.8	27.2	-20.6	99.0	-19.8	41.6
195000-215000	-8.3	23.6	-20.6	101.6	-4.0	16.8

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